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APPLIED MATHEMATICS

RESPONSE OF A SIMPLE FLOATING STRUCTURE TO UNDERWATER EXPLOSION ATTACK

by

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Erich Buchmann

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RESEARCH AND DEVELOPMENT REPORT

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ABSTRACT

The response of a simple floating target simulating a structure subjected to underbottom explosion attack has been determined and correlated with various phases of the explosion phenomena. The target was a wooden block with a bottom consisting of an air-backed steel plate of varied thickness clamped at the edge. The velocity of the wooden block and the relative velocity of the center of the steel bottom with respect to the wooden block were measured. The motion of the center of gravity was found to be the same as that of the water displaced by the target calculated as if the target were absent. The bottom and top of the target also vibrated in a manner resembling a system of two spring-connected masses. The amplitudes of vibration could be derived from the motion of the water due to the explosion.

A few tests were made to determine the effect on the motion of installing a sponge rubber bottom on the wooden block. The maximum accelerations of the block were reduced.

INTRODUCTION

The effects of an underwater explosion on a ship are complicated. The bodily response of the ship--heaving, pitching and whipping--can be derived reasonably well from the explosion phenomena, but less is understood of the motion of the bottom in relation to the bodily response. To throw an indirect light on this complicated problem, it seemed desirable to conduct explosion tests against simplified structures with more than one degree of freedom.

The simplest structure was considered to be a suitable mass with a bottom consisting of an air-backed steel plate clamped at the edge. The mass might simulate the hull of a ship or a portion of it; the steel plate, the shell or bottom exposed to explosion attack.

The response of the simplified target was measured by recording the velocity of the mass and that of the center of the plate. This response is compared in this report with theoretical expectations. Relatively few data had been obtained when the program of tests was interrupted by more urgent work. Since continuance of the main investigation is doubtful, the available data will be reported.

THEORETICAL CONSIDERATIONS

The simplified target was a wooden block with a steel plate attached to the bottom; see Figure 1a. The bottom plate may be considered to have an effective mass m which includes some portion of the actual mass m_s of the

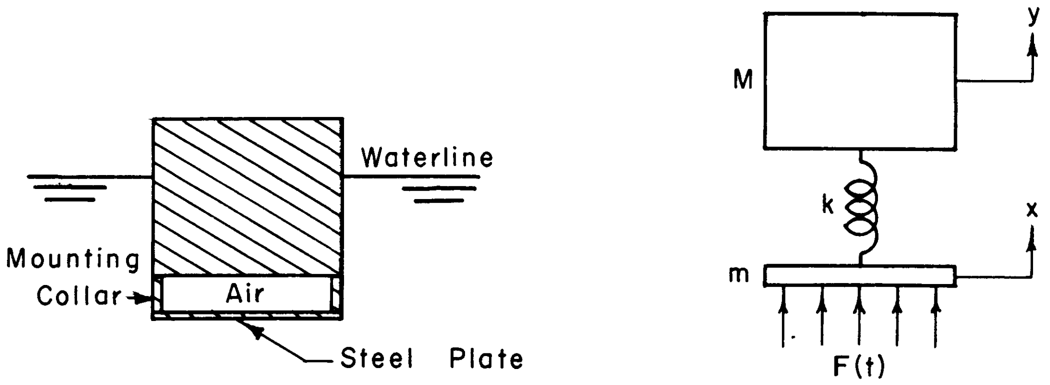

Figure 1a - Target Figure 1b - Analog

Figure 1 - Sketch of Target and Its Analog

plate and an entrained mass of water; the actual value of m is determinable from the equations to be derived. The mass m is assumed to undergo a displacement equal to that of the center of the plate and is assumed to be attached by a spring of stiffness k to another mass M. Because the bottom is a diaphragm instead of a piston, M includes, besides the mass of the block, a fraction of the mass of the steel plate and some entrained water. The simplified analog of the target thus defined is shown in Figure 1b.

An explosion attack exerts a force $F(t)$ on the bottom mass m. (The small force on the collar is neglected.) If x is the upward displacement of m and y that of M, the system (Figure 1b) obeys approximately the following differential equations:

$$m\ddot{x} + kx - ky = F(t)$$

$$M\ddot{y} + ky - kx = 0$$

If we define

$$k\left(\frac{1}{m} + \frac{1}{M}\right) = \omega^2$$

then

$$\ddot{x} + \frac{M}{M+m}\,\omega^2 (x-y) = \frac{1}{m}\,F(t)$$

$$\ddot{y} + \frac{m}{M+m}\,\omega^2 (y-x) = 0 \qquad [1]$$

If $z = x - y$, the velocity of m relative to the mass M is $\dot{z} = \dot{x} - \dot{y}$, and the differential equation for z from [1] is

$$\ddot{z} + \omega^2 z = \frac{1}{m} F(t) \qquad [2]$$

The forcing function in the very early stages is associated with the shock-wave phase of the explosion, whereas during later phases the forces and the water motion are associated with the pulsating gas bubble. In general, the period of oscillation of the target is large compared with the decay constant of the shock wave and the duration of the ensuing cavitation. It is possible, therefore, to formulate a theory describing the gross features of the motion without including the details of the action of the shock wave and of cavitation.

A rigid floating target has been observed to follow closely the average motion of the displaced water that would occur if the target were not present. If $\bar{u}$ denotes the water velocity averaged over the volume, we may write as valid during the first bubble period, according to Equation [7] in Reference 1,*

$$\bar{u}(t) = \bar{u}_{\max} \cos 1.96 \left(\frac{t}{t_{m_1}} - 0.2 \right)$$

where t_{m_1} is the half period of bubble pulsation and $\bar{u}_{\max}$ in feet per second may be calculated in the way described in Reference 2, pages 6 and 7. The value of $\bar{u}$ at time $t = 0$ represents the net impulsive velocity given to the water by the shock wave.

The force that acts on a body due to an explosion is approximately the same as the force that would act on the displaced water if the target were absent and the displaced water stood still. Hence

$$F(t) = (m_w + m_e)\, a_w = (m_w + m_e) \frac{d\bar{u}}{dt}$$

where m_e is the entrained mass associated with the displaced water mass m_w and a_w is the acceleration of the water when the target is absent.

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*References are listed on page 17.

Thus

$$F(t) = -(m_w + m_e)\,\bar{u}_{\max}\,\frac{1.96}{t_{m_1}}\,\sin 1.96\left(\frac{t}{t_{m_1}} - 0.2\right)$$

Using the abbreviations

$$\phi = \frac{1.96}{t_{m_1}}, \quad A = 1.96 \times 0.2 = 0.392$$

Equation [2] may be written

$$\ddot{z} + \omega^2 z = -\frac{m_w + m_e}{m}\,\bar{u}_{\max}\phi\,\sin(\phi\, t' - A) \qquad [3]$$

The boundary conditions at $t = 0$ are $z = 0$ and $\dot{z} = \frac{m_w + m_e}{m}\,\bar{u}_{\max}\cos A$. The latter condition results from the assumptions that the initial velocity of the top is zero and that the mass has a momentum equal to the (finite) momentum of the displaced water and its entrained mass at zero time. The solution is

$$z = \frac{m_u + m_e}{m}\,\frac{\bar{u}_{\max}}{\omega^2 - \phi^2}\left[-\phi \sin A \cos \omega t + \omega \cos A \sin \omega t - \phi \sin(\phi t - A)\right]$$

Hence

$$\frac{\dot{z}}{\bar{u}_{\max}} = \frac{m_w + m_e}{m}\,\frac{\omega^2}{\omega^2 - \phi^2}\left[\frac{\phi}{\omega}\sin A \sin \omega t + \cos A \cos \omega t - \frac{\phi^2}{\omega^2}\cos(\phi t - A)\right] \qquad [4]$$

The response of the top mass M can be obtained from the second Equation [1] by inserting the expression $z = x - y$ and integrating with the boundary condition that $\dot{y} = 0$ at $t = 0$

$$\frac{\dot{y}}{\bar{u}_{\max}} = \frac{m_u + m_e}{M + m}\,\frac{\omega^2}{\omega^2 - \phi^2}\left[-\frac{\phi}{\omega}\sin A \sin \omega t - \cos A \cos \omega t + \cos(\phi t - A)\right] \qquad [5]$$

The solutions for $\dot{z}$ and $\dot{y}$ depend mainly on the parameters ω and ϕ, i.e., on the frequency of the system and on the period of the bubble. Two limiting cases are considered:

$$\phi < < \omega \text{ and } \phi > > \omega$$

For $\phi << \omega$, Equations [4] and [5] reduce to

$$\frac{\dot{z}}{\bar{u}_{\text{max}}} = \frac{m_w + m_e}{m} \cos A \cos \omega t$$

and

$$\frac{\dot{y}}{\bar{u}_{\text{max}}} = \frac{m_w + m_e}{M + m} \left[- \cos A \cos \omega t + \cos (\phi t - A) \right]$$

Since the target floats, its mass is equal to the mass of the displaced water, and the entrained masses of the two are also approximately equal. Hence $M + m = m_w + m_e$, approximately. Accordingly, the last equation indicates that for $\phi << \omega$ the maximum value of $\dot{y}$ is about $2 \, \bar{u}_{\text{max}} \cos A$. The relative velocity $\dot{z}$ represents predominantly a motion at the circular frequency ω. Since m includes entrained mass, the variation of $\dot{z}$ with change in the mass of the bottom plate is not rapid.

With $\phi >> \omega$, on the other hand, the top moves predominantly at the frequency ω with relatively small amplitudes:

$$\frac{\dot{y}}{\bar{u}_{\text{max}}} = \frac{m_u + m_e}{M + m} \, \frac{\omega}{\phi} \sin A \sin \omega t$$

In this case the relative velocities of the top and bottom follow the water motion with some amplification:

$$\frac{\dot{z}}{\bar{u}_{\text{max}}} = \frac{m_w + m_e}{m} \cos (\phi t - A)$$

As stated earlier, the forcing function is a good approximation only up to the first bubble pulse.

TEST METHODS

A schematic diagram of the test arrangement is shown in Figure 2. The target consisted of a cylindrical wooden block, 22.6 in. in diameter, 19 in. in height, and 174 lb in weight. A 22-lb steel collar, 2 3/16 in. high,

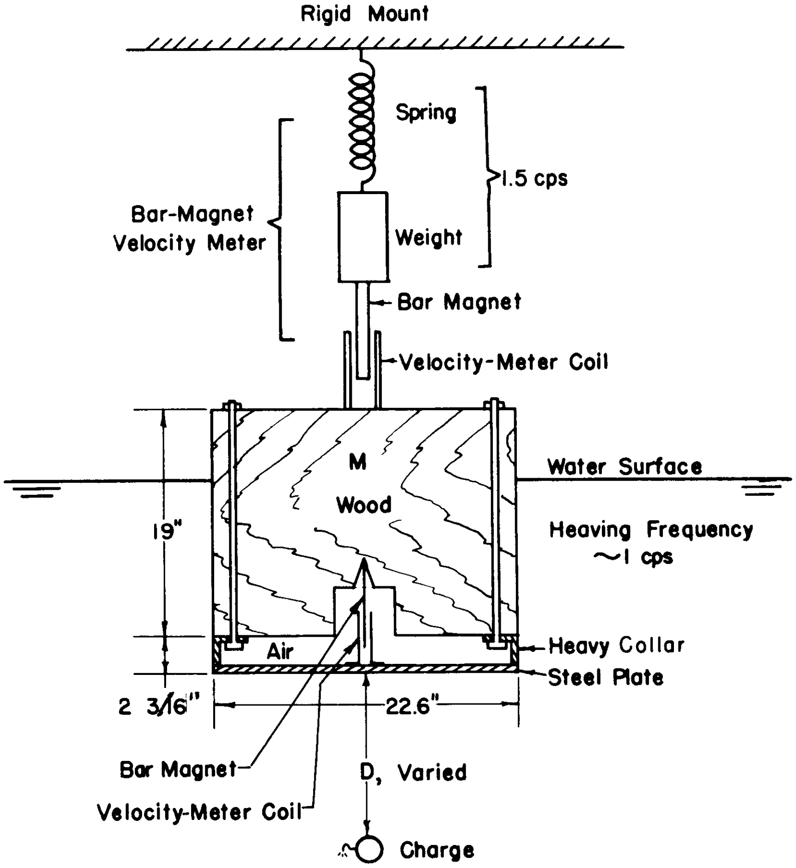

Figure 2 - Schematic Diagram of Test Arrangement

was attached to the bottom by 12 bolts. The steel plate was welded to the collar. The target was kept watertight by using a gasket between the wooden block and the collar and by coating the wood with Tygon waterproofing compound. Three different medium-steel plates were used as bottoms. They were 0.312, 0.03, and 0.0135 in. thick and weighed 35, 3, and 1.5 lb, respectively.

The response of the target was measured by two bar-magnet velocity meters.[3] One indicated the velocity of the wooden block relative to a seismically mounted mass; the other measured the velocity of the center of the steel plate relative to the wooden block. (A seismic mount having a very low frequency was used to prevent damage to the velocity meter during the very late stage of a test.) Special care was taken to keep the mass of the coil that was attached to the steel plate very small.[4] Each velocity meter was connected to a recording galvanometer, which had a sensitivity of 2.3 ma/in., in a consolidated oscillograph. The frequency response was uniform up to about 500 cps.

The target was attacked by explosions set off below the center of the bottom at varying distances. The charge usually used was an Engineer's Special detonator, equivalent to 1.25 grams of Pentolite; a few tests were made with 3, 7, and 15 grams of Pentolite plus an Engineer's Special detonator.

Some tests were conducted against the target without any bottom and with a 2 3/16-in. layer of sponge rubber within the heavy collar.

TEST RESULTS

The addition of various structural components to the top mass of the target caused a gradual change in the velocity traces under explosion loading as shown in Figure 3. On the right-hand side are sketches of four target arrangements, the target in all cases having neutral buoyancy. In line with each sketch is a velocity-time trace for the target top during attack by 16.25 grams of explosive located 60 in. below the bottom of the target. For arrangement (d) there is an additional trace of the relative velocity of the center of the steel plate with respect to the target top. Upward deflection of the trace indicates upward velocity, except for the lowest trace where downward deflection indicates upward velocity. All traces show the target response extended beyond the first bubble contraction. Study of the oscillograms of Figure 3 for the various situations leads to the following observations:

(a) Top mass alone. The velocity curve shows an initial impulsive loading caused by the shock wave, followed by a decrease of the velocity ascribed to cavitation. The target follows the water motion caused by the

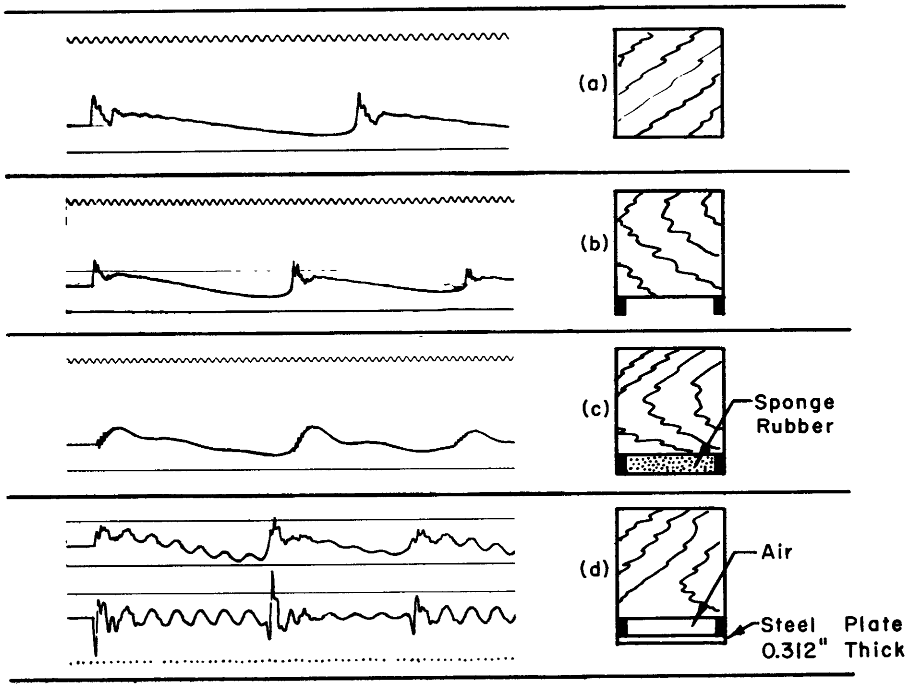

Figure 3 - Velocity Traces for Explosion Attack on Gradually Changed Targets

For explanation, see the text, pages 7 and 8.

pulsating gas bubble after cavitation is presumed to have disappeared.

(b) Top mass plus collar, the space within the collar being filled with water. The trace is similar to that obtained from the top mass alone.

(c) Top mass plus collar, area within collar filled with sponge rubber. This arrangement was intended to simulate an air-filled volume within the collar not closed by a diaphragm. The trace indicates no initial impulsive loading; instead the target moves with increasing velocity upward and then follows the water motion. There is a suggestion of an oscillation of relatively low frequency which may be due to the presence of the sponge rubber.

(d) Top mass with collar to which a 0.312-in. steel plate is attached. The upper trace, showing the velocity of the top mass of the target, is similar to that of arrangement (c), with a higher frequency superimposed. The bottom trace indicates an initial upward velocity (downward in the record) of the steel plate, which decreases rapidly, leaving the plate to vibrate with the same higher frequency as the target top but out of phase by 180 deg.

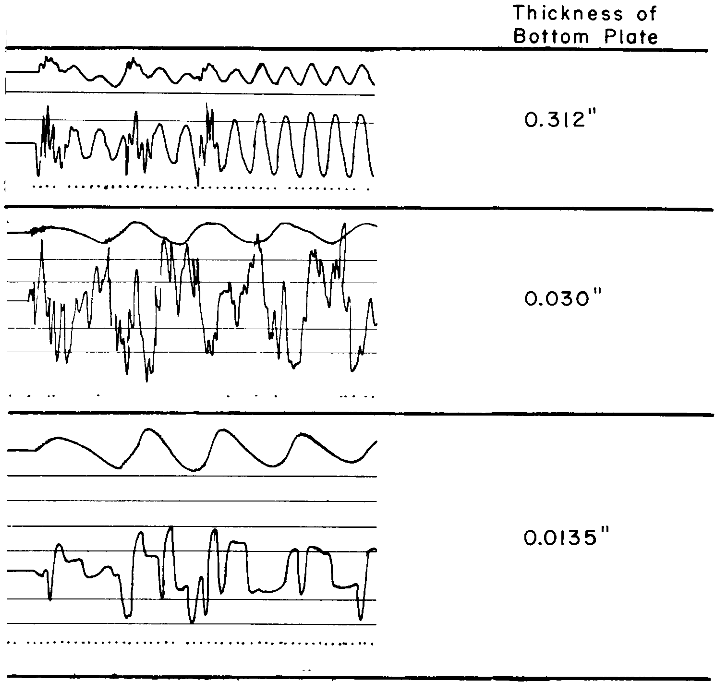

Figure 4 - Velocity Traces of Target with Varied Thickness of Bottom Plate

The charge was equivalent to 1.25 grams of Pentolite at 40 in. from the target bottom. The upper curve always refers to the top of the target; the lower curve to the velocity of the steel plate relative to the main body of the target. The time scale is 400 pulses per second. The traces were recorded at approximately the same film speed.

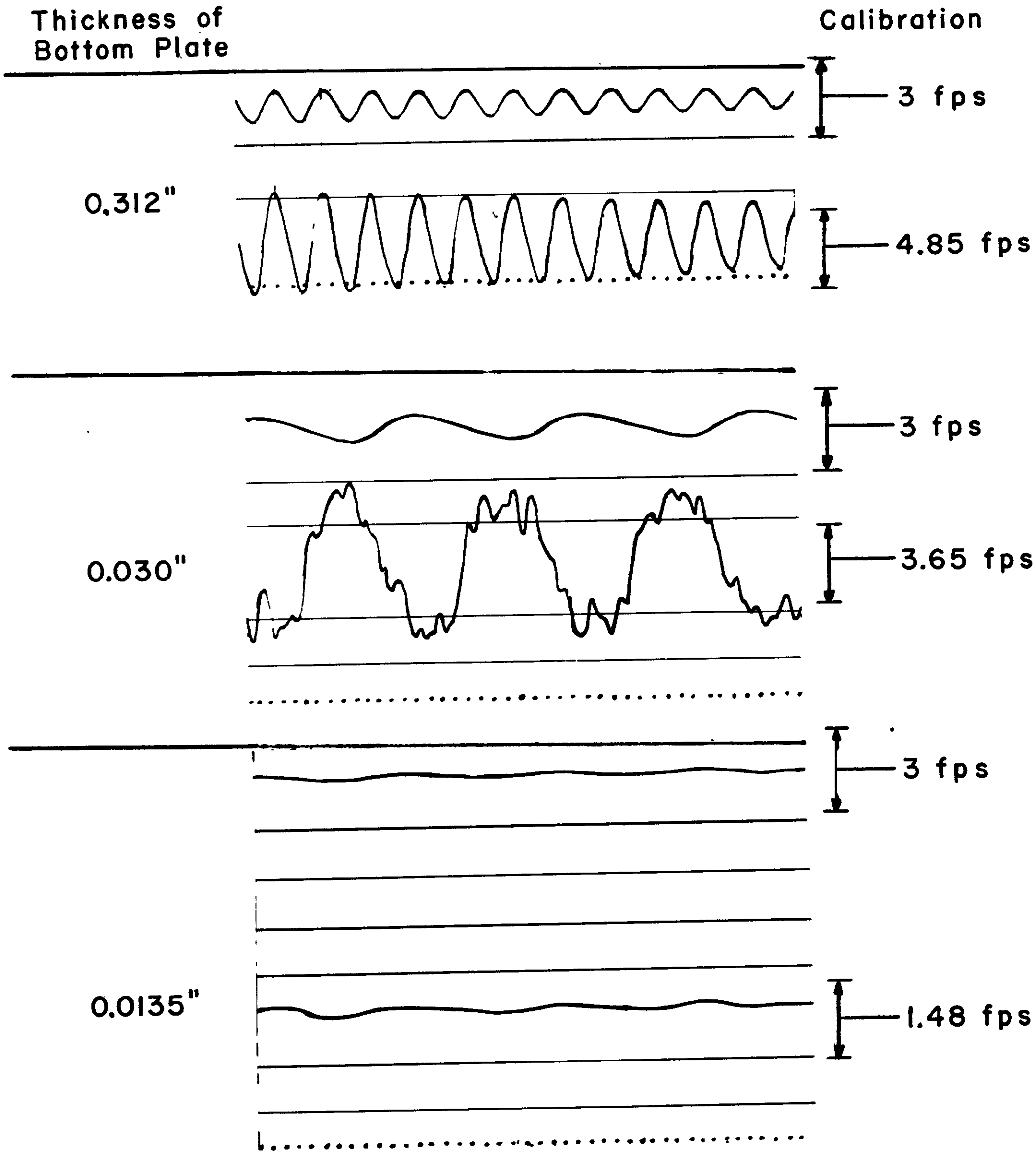

Figure 5 - Velocity Traces of Target with Varied Thickness of Bottom Plate About 60 Milliseconds After Explosion Attack

The charge was equivalent to 1.25 grams of Pentolite at 40 in. from the target bottom. The upper curve always refers to the top of the target; the lower curve to the velocity of the steel plate relative to the main body of the target. The time scale is 400 pulses per second. The traces were recorded at approximately the same film speed.

Additional oscillograms corresponding to arrangement (d) are reproduced in Figure 4. Three sets of velocity traces are shown for targets with bottom plates 0.312-in., 0.03-in., and 0.0135-in. thick. The upper traces represent the velocity of the top mass relative to the seismic weight the lower traces correspond to the velocity of the center of the bottom plate relative to the top mass.

If the high-frequency response at about 1000 cps and higher is neglected (the velocity meters exhibited increased sensitivity at that frequency), the curves show similar features. The upper traces show a long-duration trend corresponding to the water motion associated with the pulsating gas globe. This might be considered the predominant motion in the heaving motion of the system on which a cyclic motion is superimposed.

The bottom plate follows the cyclic motion, clearly visible for the 0.312-in. plate. The traces for the 0.03-in., and 0.0135-in. plates show basically the same trend but include some additional high-frequency response.

Figure 5 shows that, after the explosion loading has died down, the traces become more regular and have almost constant amplitudes. The traces shown are from the same tests as those in Figure 4 but start about 60 msec after the beginning of the explosion attack. Top and bottom vibrate with the same period but 180 deg out of phase. The traces indicate further that the motion is not quite symmetrical, the asymmetry being greater for the 0.03-in. and 0.0135-in. plates than for the 0.312-in. plate. Note the inequality of consecutive half periods in the traces for the 0.03-in. plate.

DISCUSSION OF RESULTS

The velocity traces for the target top and for the bottom plate indicate that the response to an underbottom explosion attack resembles the response of a system of two masses connected by a spring. The results can be compared with theoretical predictions if the values for the total effective mass m of the bottom and the frequency ω are known.

As the total momentum of the vibration in such a system is zero at later stages when no outside forces are acting on the system, we have

$$M\dot{y} + m\dot{x} = 0$$

or

$$m = -M\frac{\dot{y}}{\dot{x}} \qquad [6]$$

If m and M do not vary during a cycle, the ratio of $\dot{y}$ to $\dot{x}$ will not vary. The velocity $\dot{y}$ is recorded directly and may be taken from the velocity traces. The velocity $\dot{z}$ is also measured. Then $\dot{x} = \dot{y} + \dot{z}$.

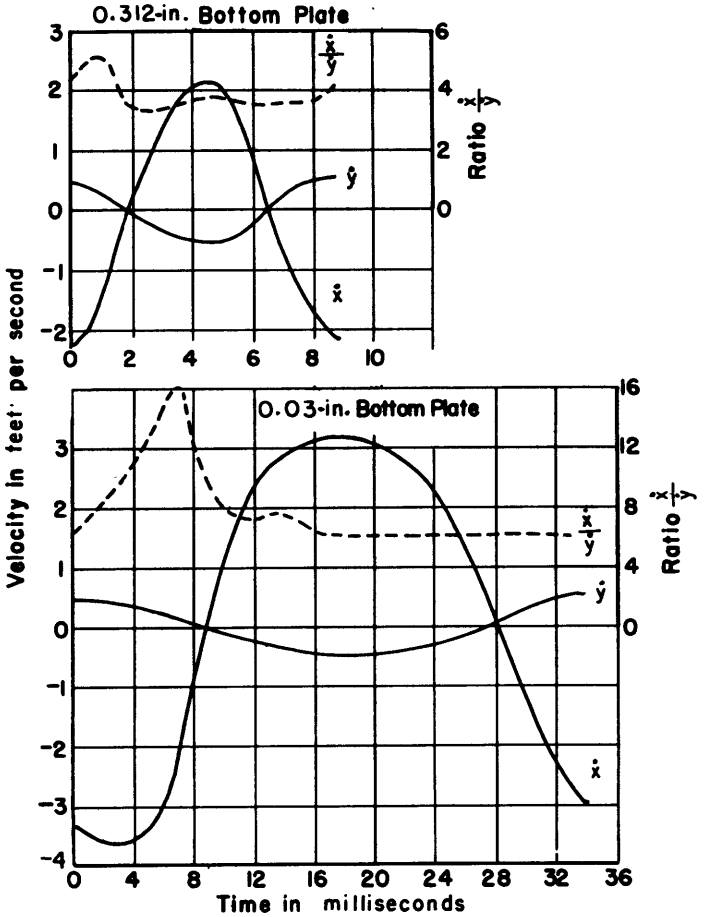

Figure 6 - Top Velocity $\dot{y}$, Bottom Velocity $\dot{x}$, and Ratio $\frac{\dot{x}}{\dot{y}}$ during One Vibration Period for 0.312-Inch and 0.030-Inch Bottom Plates

The curves are for a late stage in the motion when the explosion forces have died down.

Values of $\dot{y}$ and $\dot{x}$ for the targets with 0.312-in. and 0.03-in. bottom plates are plotted against time for one vibration period in Figure 6. The graph also includes the ratio $\dot{x}/\dot{y}$. This ratio apparently varies as the downward velocity of the plate is reduced to zero but stays fairly constant during the remaining part of the period. Thus the bottom mass m in Equation [6] stays fairly constant during the greater part of a period and decreases for a short time, possibly due to cavitation effects at the center of the bottom plate. The effect is more pronounced for the 0.03-in. than for the 0.312-in. plate. Such cavitation may account for the asymmetric nature of the motion. No ratio is evaluated for the target with a 0.0135-in. plate.

In that case, the bottom plate undergoes rapid and abrupt velocity changes. This might be due to the occurrence of buckling induced by distortion in the plate, caused by the welding process. The data for the other plates are considered more significant.

From the observed ratio $\dot{x}/\dot{y}$, m can also be calculated if M is known. For this purpose, M was taken as the top mass, contributions from the masses of the bottom plate and entrained water being neglected; because of this approximation the values of M and m may be perhaps 10 percent low.

The frequency ω also can be obtained from late stages when all motions are considerably decreased. Values thus obtained for m and ω are summarized in Table 1.

TABLE 1

Frequency, Total Bottom Mass, and Mass of Bottom Plate for Target with Various Bottom Plates

Thickness of Target Bottom in.	Frequency ω rad/sec	Approximate Bottom Mass m lb	Mass of Bottom Plate lb
0.312	700	60	35
0.030	210	33	3

With the values for ω and m thus obtained, it is possible to calculate the velocity response of the target by using Equations [4] and [5]. The results for an explosion attack by Engineer's Special detonators against a target with a 0.312-in. or a 0.03-in. bottom plate are shown in Figure 7. The proportionate velocities of target top and bottom are plotted against time. A comparison with the measured response in Figure 4 shows clearly the similarity of the traces. Similar curves may be obtained for various charge sizes.

The velocity history of the target top may now be used for further comparisons with the calculated results. The ratio of the first maximum upward velocity to the maximum average particle velocity of the displaced water is, according to calculation, a constant for given charges at stand-off distances not too close to the target. This constant is about 1.9 for attack by Engineer's Special detonators against a target bottom 0.312-in. thick. Its value is almost the same for charges up to 16.25 grams, the largest charge used during these tests, and should be the same for all larger charges. For the targets with thinner bottom plates, the calculated ratio is about 1.6. Table 2 summarizes the results obtained from these tests.

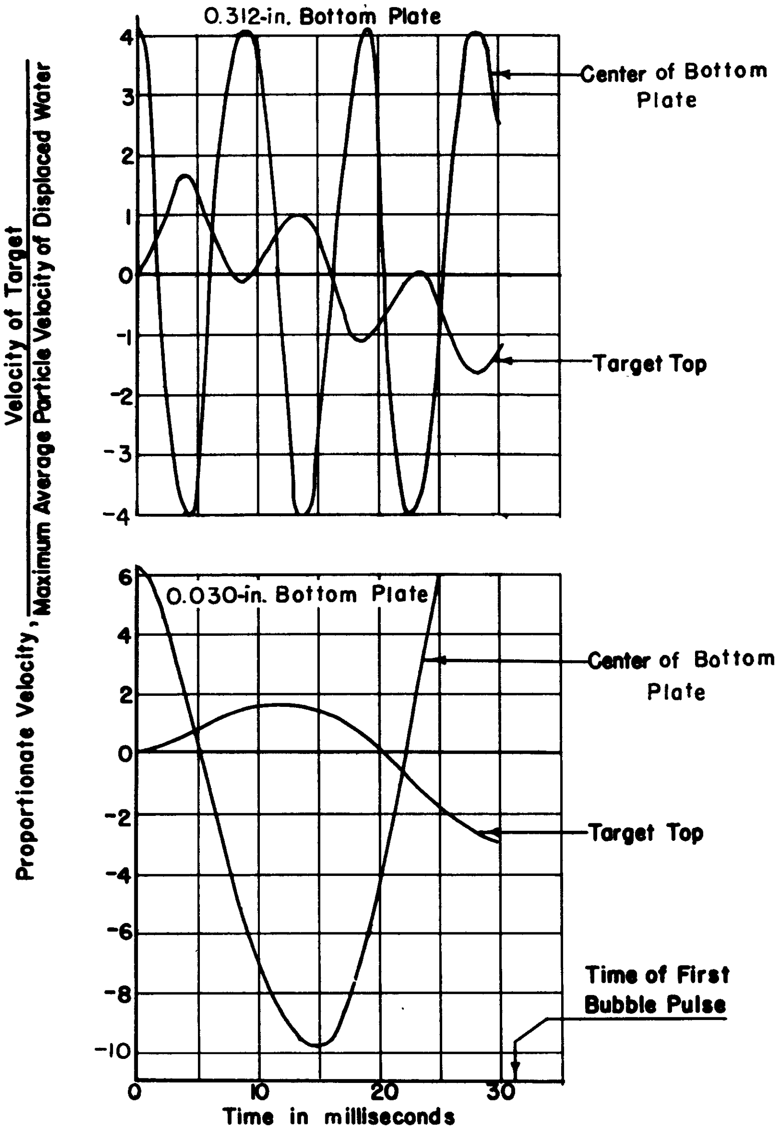

Figure 7 - Calculated Proportionate Velocity Response of Target Top and Relative Velocity Response of Target Bottom to Explosion Attack by 1.25 Grams of Pentolite during First Bubble Pulsation

TABLE 2

Ratio of First Maximum Velocity of Target Top to Maximum Particle Velocity of Displaced Water

Distance of Charge below Target in.	Thickness of Target Bottom in.	Maximum Particle Velocity of Water u_{max} ft/sec	First Maximum Velocity of Target Top y_m ft/sec	$\frac{y_m}{u_m}$
60	0.312	0.36	0.92	2.55
40	0.312	0.68	1.4	2.05
30	0.312	1.10	1.8	1.63
20	0.312	1.8	3.5	1.94
15	0.312	2.5	4.9	1.96
10	0.312	3.6	7.0	1.94
8	0.312	4.2	8.2	1.95
4	0.312	5.3	11.0	2.07
60	0.030	0.38	0.55	1.45
40	0.030	0.69	0.98	1.44
30	0.030	1.10	1.65	1.50
60	0.0135	0.40	0.57	1.43
40	0.0135	0.72	1.15	1.60
30	0.0135	1.10	1.7	1.54

The last column indicates that the ratio is generally in the range expected from the calculations. A few tests with larger charges made at 60-in. standoff also showed consistency with the calculations.

The first peak velocities of the target top are plotted against distance in Figure 8. Also included in this plot are the maximum velocities for the heaving or center-of-gravity motion. The indicated points correspond to measurements on a floating block, and the curve is calculated for the motion of the displaced water. The graphs show agreement of the measurements with the calculations.

The tests, in general, justify the assumptions made in developing theoretical formulas. The initial loading causes the bottom plate to accelerate inward so that maximum velocity occurs at about 30 μ sec. Subsequently, because of cavitation, the velocity would decrease in a relatively short time.

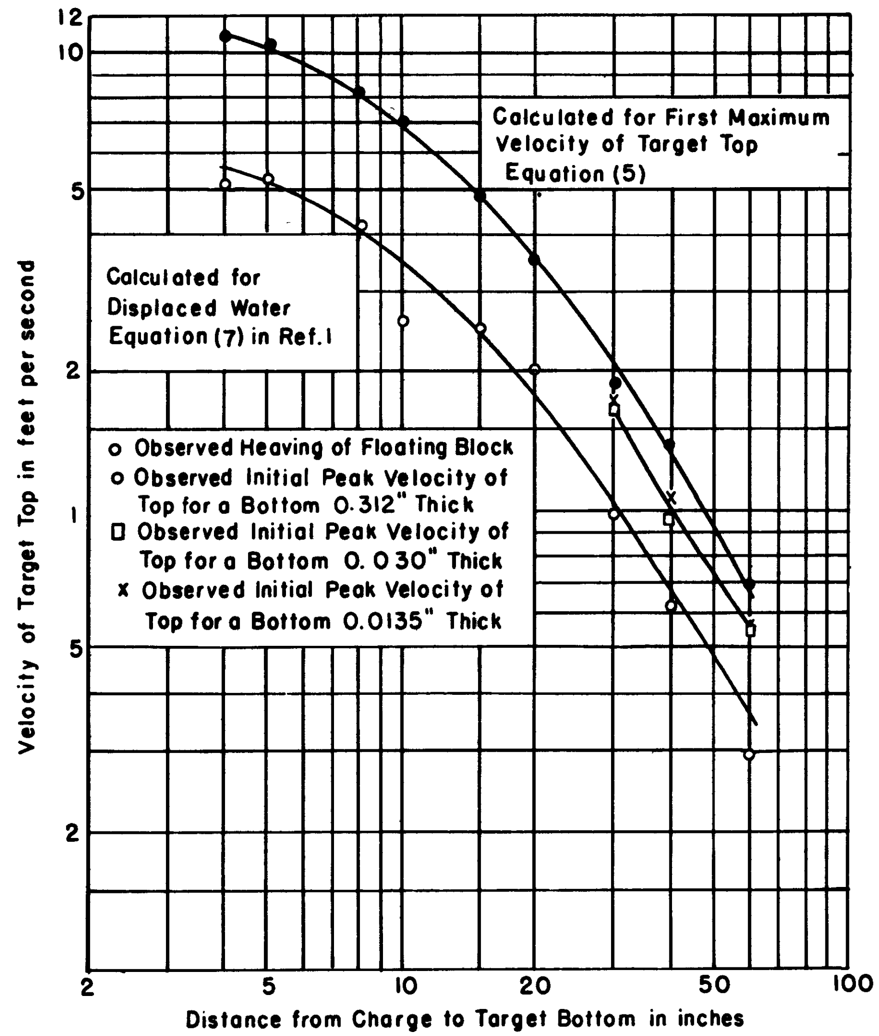

Figure 8 - Initial Peak Velocity of Target Top and Maximum Heaving Velocity
The charge was an Engineer's Special detonator.

The later loading by the water motion has been, in effect, calculated fairly accurately on the assumption that the force changed so slowly that reduction of the pressure due to diffraction is always practically complete. The subsequent particle velocity of the water as the gas globe expands, which actually is the result of the total pressure-time history up to the time considered, is fairly well-known from a time $t = 0.003\ t_{m_1}$ and later,[5] which corresponds in these tests to an average time of less than 100 μ sec. It increases rapidly to a maximum. The approximate formula for the particle velocity of the water used in these calculations is justified because the periods of the target vibrations were much larger than the decay constant of the actual initial shock-wave loading.

A layer of sponge rubber 2 in. thick at the bottom of the target affects the motion of the target top considerably. The target starts moving upward slowly and rises to a peak velocity. The slope of the velocity curve during this period is considerably less than that for the target with a heavy steel plate as a bottom or with no bottom plate at all, i.e., there is a large reduction in the initial acceleration. Targets without a steel collar but with sponge rubber at the bottom showed a completely smooth rise of velocity without initial vibrations. (Traces are not shown in this report.) The change of velocity at the bubble pulses is also very smooth.

Subsequently, the target top closely follows the water motion with a slight indication of a superimposed frequency; see Figure 3. The ratio of the initial maximum velocity to the maximum particle velocity of water was measured to be 1.3 for 16.25 grams of Pentolite. Similar effects were noted in tests with sponge-rubber layers 1/2 and 3/4 in. thick and with charges ranging up to 25 grams.

The sponge rubber thus eliminates the great acceleration associated with the initial impulsive loading, but the maximum velocity still somewhat exceeds that of the displaced water.

In terms of full-scale situations, sponge rubber or an air layer on the bottom of a ship, such as a minesweeper, which is subject to repeated explosion attack, might tend to reduce shock damage. Further exploration of the protection possibilities afforded by sponge rubber or air layers will be conducted in connection with other projects at the Model Basin.

CONCLUSIONS AND RECOMMENDATIONS

Underbottom explosion tests were conducted against a floating structure representing an idealized model of the hull structure of a ship The target vibrated much like a system of two masses connected to each other by a spring.

Underbottom explosion attack caused the target to respond in a rigid-body heaving motion and in vibrations involving relative movement of the target members against each other.

The heaving or center-of-gravity motion of the floating structure follows closely the average motion the displaced water would have in the absence of the target.

The longer term effects of the explosion on the target bottom and on the target as a whole can be calculated on the assumption that the water motion around the pulsating gas bubble is incompressive.

The shock wave has only a small immediate effect on the top mass, and its effect on the bottom plate quickly becomes reduced. The pressure acting subsequently on the bottom plate depends on the water motion of the pulsating gas bubble.

The vibratory motion has amplitudes which depend on the natural frequency of the structure. Calculated values of the velocity amplitudes agree with the measured values.

With an air backed bottom plate present, the initial, violent, overall response of the target is suppressed considerably as by a cushion. The initial accelerations of the top are largely reduced, especially with a flexible bottom. However, the velocity and displacement of the top are greater than those for heaving alone.

A sponge-rubber bottom is very effective in reducing the acceleration and vibration of the top, eliminating completely the initial impulsive effects of the shock wave.

This result suggests a possible means for shock protection of ships repeatedly exposed to explosion attack such as minesweepers. A layer of material similar to sponge rubber or an air cushion of reasonable dimensions should reduce initial accelerations due to the shock waves and, thus, shock damage to equipment. The protection possibilities of sponge rubber or air layers will be further investigated in connection with other projects at the Model Basin.

ACKNOWLEDGMENTS

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1. Underwater explosion damage – Theory
2. Ship hulls – Structural analysis – Model tests
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